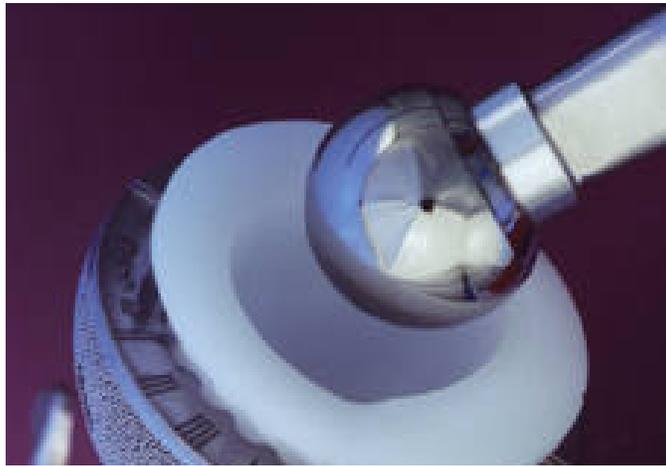


# Artificial Hip Joints: Applying Weapons Expertise to Medical Technology



*Oxidized zirconium is an excellent material for the artificial femoral heads used in hip replacements, but it cannot be easily shaped by conventional grinding. We drew on our expertise in high-precision machining to show one manufacturer how to apply precision, single-point turning to the manufacture of zirconium femoral heads.*

**M**ATERIALS fabricators at LLNL have spent several decades developing sophisticated precision machining techniques, such as single-point diamond turning, in connection with past weapons research. More recently, we are using these skills to assist U.S. manufacturers in meeting technological challenges. This article tells the story of how LLNL machining specialists transferred expertise gained through weapons

research to the field of medical technology—particularly the manufacture of improved, innovative prosthetic hip joint replacements.

## **The Medical Problem**

Hip replacement has become increasingly commonplace as the medical technology has improved, as life spans increase, and the population ages. It is most commonly performed to reduce the pain and

immobility of arthritic patients over 55 years of age. In 1993, an estimated 129,000 people received total hip replacements in the U.S.<sup>1</sup> Sales of the prostheses alone generated between \$600 million and \$800 million in 1993.

In a total hip replacement, the pelvic bone must be cut away and a polyethylene cup fitted to receive the artificial femoral head.<sup>2</sup> This head is often attached by an artificial stem to the altered femoral bone. Unlike most

other forms of surgery, this procedure is followed by an intensive course of antibiotics and immunosuppressives. Hip replacement surgery is not to be undertaken lightly; yet the nonsurgical alternative (medication) for long-term management of arthritis is very expensive over the long term and may leave the patient debilitated or disabled.

Artificial hip joints, however, undergo a very gradual wear process and have a limited lifespan. The hip joint transfers very large loads. The hip joints carry the weight of the upper body, and the legs transfer the forces of locomotion to the torso. In spite of these conditions, an artificial hip joint can perform well for 15 years or more, depending on type and level of activity. The younger the patient at the time of replacement, the greater the likelihood a repeat operation may have to be considered in a normal lifespan.

Moreover, as the polyethylene cup wears and third body debris is produced, the metal surface of an artificial femoral head may become rougher. This roughness in turn may promote further abrasive wear of the polyethylene cup. (Figure 1 shows an exaggerated schematic of roughness.) Wear produces debris. Although the debris particles are very small, usually less than a micron across, they are not tolerated by the human body. The body's normal cell growth and regeneration decrease in their vicinity.

Eventually, then, the question of another replacement arises, but the decision is complicated by such factors as the age and health of the patient and the cost of the artificial piece and of the operation. There are therefore strong health and economic incentives to lengthen the useful life of artificial hip components.

## The Materials Solution

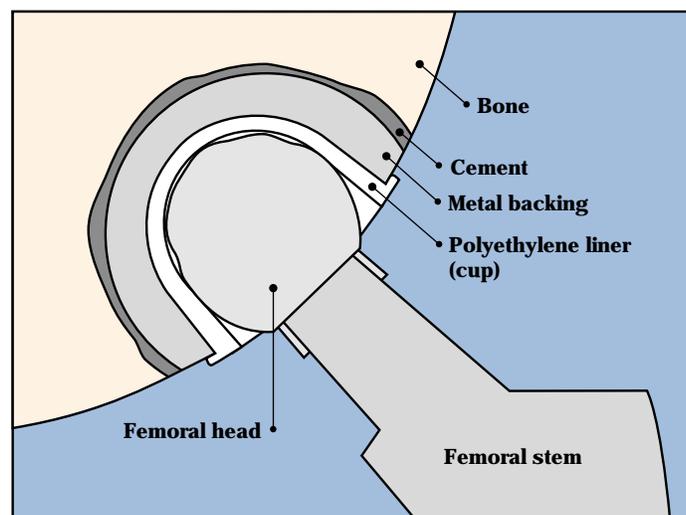
Smith and Nephew Richards, an established firm based in Memphis, Tennessee, with a wide inventory of prosthetic implants and synthetic replacements for bones in the body, is a major supplier of artificial hip joints. Historically, they have offered three artificial femoral heads, one made of cobalt–chrome, the others of a solid ceramic (alumina and zirconia,  $\text{Al}_2\text{O}_3$  and  $\text{ZrO}_2$ ). The ceramic is extremely wear-resistant and wears away the polyethylene cup much more slowly than the cobalt–chrome head but is more expensive to manufacture. Smith and Nephew Richards' researchers were aware that the metal zirconium can be oxidized to acquire a hard zirconia ceramic surface. They reasoned that if zirconium metal could be shaped to exact dimensions by machining, they could combine the best of both technologies: they could fabricate the femoral head at a relatively lower cost than that of a solid ceramic but achieve the same wear resistance. Zirconia's lower coefficient of friction than cobalt–chrome's for

lubricated sliding against polyethylene and thus lower rate of wear on the polyethylene cup is expected to lengthen the useful life of the unit. Even if it lasted only a few years longer, it could mean the difference, for a hip-replacement patient in his or her thirties or forties, between facing one rather than two additional replacement operations in a lifetime.

## The Process Problem

Initially, Smith and Nephew Richards tried unsuccessfully to use traditional hardware and conventional techniques to grind the zirconium into the spherical femoral head. Grinding typically works best on hard, brittle materials, but zirconium is a relatively soft, ductile material. Experience has shown that ductile materials are difficult to grind; the material builds up on the grinding wheel and produces a rough, galled surface on the workpiece.

Some of the initial trials on zirconium parts that Smith and Nephew Richards' fabricators attempted to grind were rough and



**Figure 1.** Schematic showing the geometry, close up, of an insufficiently smooth ball (head) in a cup. The roughness is enormously exaggerated to show how the head fails to distribute pressure uniformly, creating pressure points that will become wear points.

out-of-round, and the grinding wheels lasted minutes instead of their normal wear life of hours or days. When consulted, neither the grinding machine manufacturer nor the grinding wheel manufacturer had a solution.

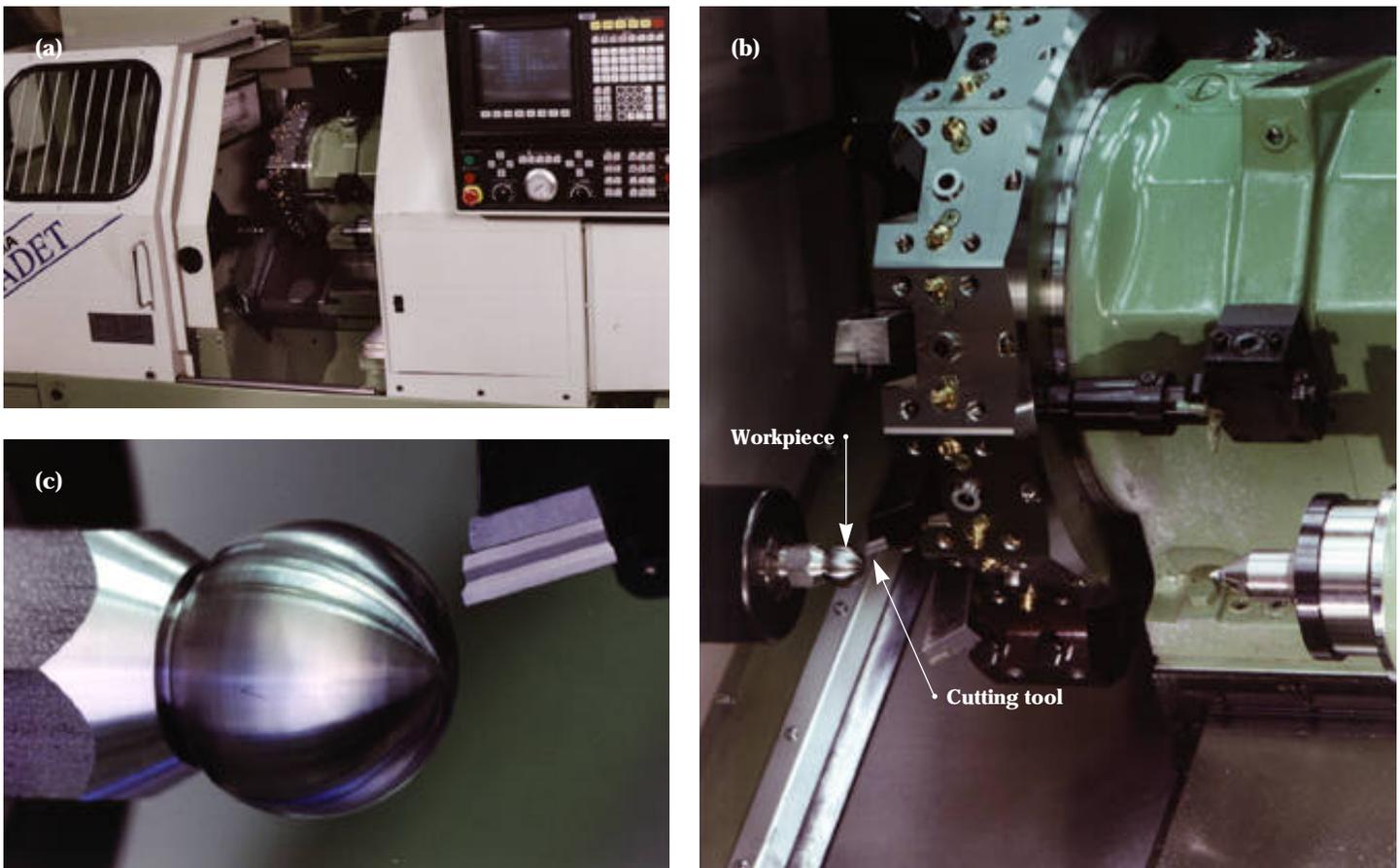
Through hearing about our CRADA (cooperative research and development agreement) with COM (the Consortium of Optical Manufacturers), Smith and Nephew Richards learned that we at LLNL have decades of experience grinding and that we have a comprehensive

grinding capability. They described their problems to us, and we visited their plant to better understand the problems and to see first hand what type of equipment they use and products they manufacture. We signed an LLNL research agreement with Smith and Nephew Richards to do the work under the U.S. Department of Energy's National Machine Tool Partnership (an initiative engaging the efforts of several national laboratories to improve the competitiveness of U.S. firms), and set about evaluating their

fabrication processes. Our research on zirconium led us to the conclusion that grinding was not the most effective material removal process.

### The Process Solution

Since the femoral head is spherical, we used our expertise in precision turning acquired through years of fabricating spherical components for weapons research. In simple terms, precision turning is a point-defined process that draws a single hard, pointed tool across a rotating surface



**Figure 2.** Three views of the lathe, identical to a machine in the Smith and Nephew Richards shops. (a) The safety enclosure has been rolled open to reveal the workbay; also visible are the computer numerical controls. (b) The spherical workpiece, lower left, is dwarfed by the tool carousel, which can hold a dozen cutting tools at a time (five tool holders are visible). (c) A workpiece and a cutting tool. The two are brought into contact by precise control of their relative positions, and the workpiece is rotated against the cutting tool.

in a highly controlled manner. For our weapons work, we have had to achieve contour accuracy to within 25 to 50 nm (1 to 2 millionths of an inch or 1000 times smaller than a human hair). We also developed the compensated tool paths and inspection hardware and processes to produce these very accurate spheres.<sup>3</sup>

The Smith and Nephew Richards' assignment was an excellent opportunity to transfer our knowledge directly from weapons work to an application in industry. Through testing, we confirmed that the single-point turning process would work for their purposes. We requested a list of the machine tools that Smith and Nephew Richards possessed and cross-checked it with the tool inventory at the Lab. We identified one semiprecision machine tool, a CNC (computer numerical control) lathe, that could make the parts and that was present in both the firm's plant and at the Lab. We had to demonstrate not only that single-point turning could machine the ductile zirconium, but also that the lathe could achieve Smith and Nephew Richards' standards of size, contour, and surface finish.

Contour is a very stringent requirement for Smith and Nephew Richards' application. The relationship between the contour of the femoral head and the contour of the polyethylene cup in which it rides greatly determines the rate of wear. Pressure within the joint has a first order effect on wear. Controlling contour errors will provide reduced (uniform) pressure by maximizing the area of contact. Smith and Nephew Richards' dimensional requirements for contour accuracy were on the order of 5  $\mu\text{m}$ . The company wanted the femoral head to have an  $R_a$  (roughness average)

surface finish of about 0.25  $\mu\text{m}$  *before* it is polished. Polishing then produces about a 25- to 50-nm  $R_a$  finish before the head undergoes the oxidation process that creates the ceramic layer of zirconia. (Just as ductile materials, such as zirconium, do not submit well to grinding, they are difficult to polish; they tend to sleek and gall. Accordingly, pre-oxidization polishing is done more lightly than post-oxidation polishing.)

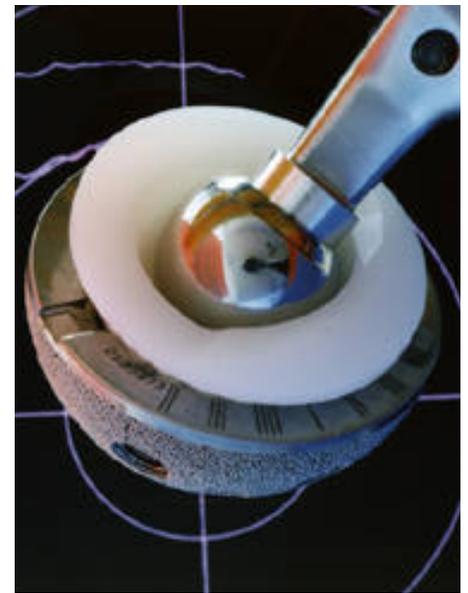
After the zirconium head is polished, it is oxidized at an elevated temperature and forms a zirconia ( $\text{ZrO}_2$ ) layer. (Oxidation turns the outer zirconium layer into zirconia; the process is accelerated by heat and the presence of certain gases.) Oxidation does not make the head smoother, only harder, and makes the resulting zirconia, like its ceramic counterpart, easier to polish to a very smooth surface.

Using their material, we produced femoral heads and other workpieces to their specifications on the CNC lathe (see **Figure 2**). We used cutting tools that were made or altered to the Laboratory's specifications (such as more exacting standards for tool nose contour) and that have since become readily available to the precision machining industry. We used a two-step turning process. The first step results in a contour that falls short of the client's specifications by a factor of two. The second step encompasses a process that LLNL has refined using inspection feedback to produce a compensated tool path: that is, a tool path that corrects for all repeatable machine errors. Typical machine errors might include nonstraightness and misalignment of machine slideways. The two-step process is the key to producing workpieces

with the accuracies down to the limitations of the machine.

## Ultraprecision Measurement

The femoral head shown in **Figure 3** is one that we fabricated and sent to Smith and Nephew Richards for polishing. They then returned it to us so that we could measure it to be sure the polishing had not degraded the contour. Our equipment is among the world's most capable for measuring contour, size, and surface roughness. **Figure 4** shows one of our devices, a small-radius gauge that measures contour by means of a linearly variable differential transformer (LVDT) probe. The accuracy of the small-radius gauge system is 25 nm. **Figure 5** shows a contour error plot generated by the small-radius gauge's data acquisition



**Figure 3.** This zirconium head has been oxidized to acquire a zirconia outer layer, which was then polished. The head has a 28-mm diameter. The stem is a titanium alloy (Ti-6Al-4V).

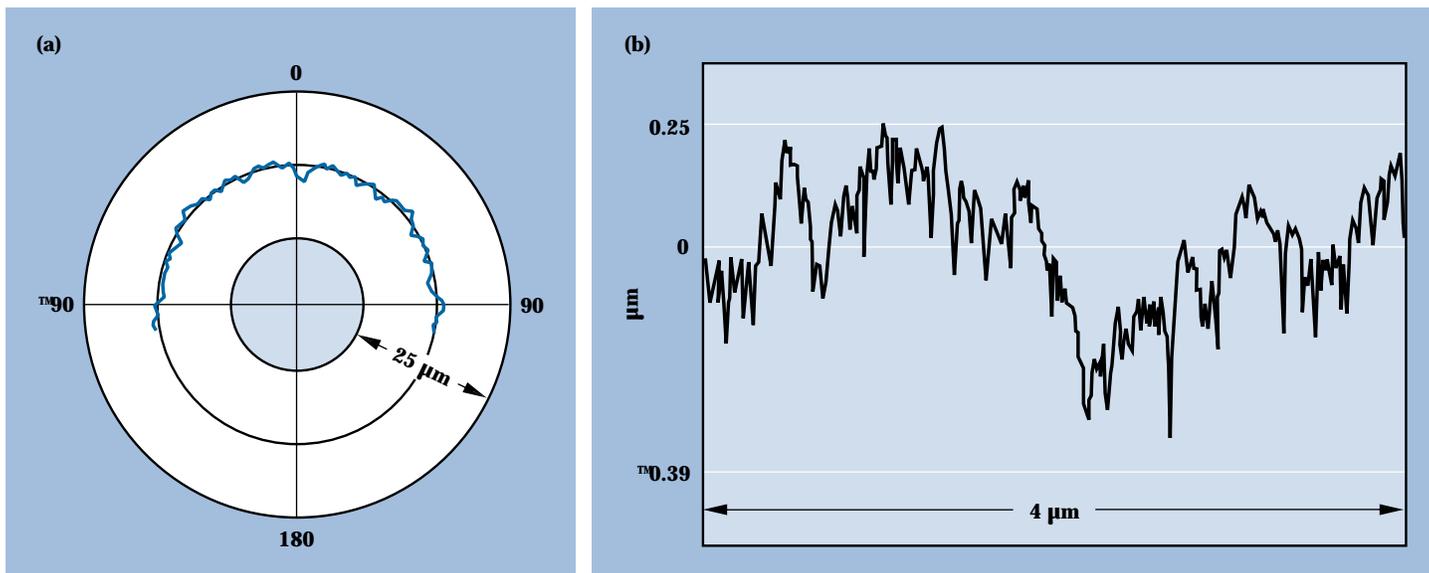
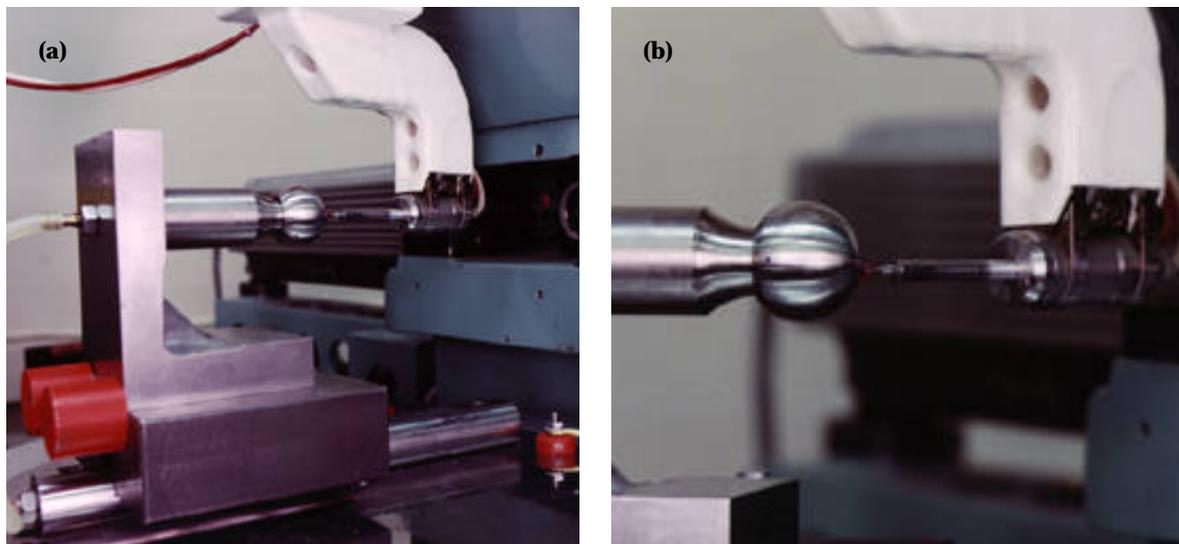
computer and a surface-roughness trace generated from a profilometer.

Having sent them back parts that we had measured for size, contour, and surface roughness, we undertook a secondary collaboration with Smith and Nephew Richards through the

National Machine Tool Partnership Program. We developed a set of standards for Smith and Nephew Richards; we also performed measurements on ten parts (cobalt-chrome and ceramic femoral heads) that they supplied to us. They used

these measured pieces to cross-check their inspection equipment and to improve further the accuracy of their measurements of precise contours and spherical shapes. They then had confidence that they could measure certain aspects of these parts, like

**Figure 4.** (a) The small-radius gauge, a commercial machine that LLNL upgraded: we added a precision air-bearing spindle, a laser interferometer position-feedback system, and a data-acquisition computer. (b) Closeup of a laser stylus attached to the air-bearing LVDT probe designed and built by LLNL. The system can measure the contour of workpieces to 2.5 nm.



**Figure 5.** (a) Plot generated by the data-acquisition computer showing contour errors generated in the single-point turning process. (Note that the distance between the inner and outer circles is 25 μm.) (b) A trace showing the roughness of a single-point turned head. The roughness average ( $R_a$ ) is 0.12 μm. The white line, at 0, represents a theoretical ideal smooth surface.

contour, on their gauge with known certainty. The minor discrepancies between our measurements and theirs quantified the uncertainty of their inspection process.

Several U.S. companies and tens of companies worldwide make femoral heads. Each firm has its own specifications and standards. It must be said that the industry produces workpieces that are, for the most part, extremely accurate spherical components. The specifications for contour and surface roughness are very stringent and have motivated these companies to develop advanced manufacturing efforts. Some pieces, made from solid ceramic, have a contour accuracy of 0.25  $\mu\text{m}$ .

### The Deliverable

We presented Smith and Nephew Richards with a "turnkey" package: step-by-step procedures, complete documents on the computer-controlled toolpath program, and an LLNL design for a specialized toolholder that provides fine control over tool height. We qualified our process by producing parts that met their specifications.

### Summary

Hip replacement surgery is performed most often to relieve the pain and immobility resulting from arthritis. Although current artificial hip systems work quite well, reducing the slow rate of wear can further improve the success of the operation. An improved, more cost effective bearing surface can be produced by

using oxidized zirconium alloy technology. There are health and financial incentives for developing a device that optimizes longevity and affordability.

The materials scientists at Smith and Nephew Richards, an established manufacturer of prosthetic devices, decided that a femoral head made of zirconium would combine the lower production costs of metal heads with the much greater longevity (less wear) of ceramic heads, because zirconium, a metal, can be oxidized to acquire a surface layer of zirconia, a ceramic. Smith and Nephew Richards' machinists, however, encountered difficulties in grinding zirconium heads to the needed size, contour, and smoothness. Having learned of the Laboratory's accomplishments in machining to extremely high precision, Smith and Nephew Richards and LLNL entered into a research agreement under the National Machine Tool Partnership to explore solutions to their manufacturing problem.

We at the Lab soon established that grinding was a rather difficult method for removing material compared to turning/cutting. The ideal technique is precision single-point turning, one that we have decades of experience with through weapons work. We located a turning machine at the Lab that is identical to one that Smith and Nephew Richards uses and turned some pieces on it to their specifications. We delivered to Smith and Nephew Richards a process, a design for a custom workpiece holder for high-precision single-point turning, and the software

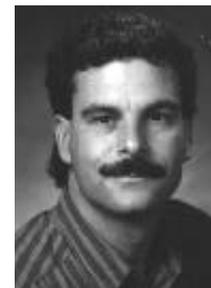
for generating the compensated tool paths. In the course of this work, Smith and Nephew Richards discovered that they could improve upon their methodology for measuring sphericity and size using the expertise of LLNL. By measuring the same pieces at both sites and comparing the results, we quantified the maximum accuracies that they could achieve with their equipment.

**Key Words:** National Machine Tool Partnership; precision engineering; single-point turning.

### Notes and References

1. *Orthopedic Network News* 5(3), 1-5.
2. B. Friedman and A. Elixhauser, "Increased Use of an Expensive, Elective Procedure: Total Hip Replacements in the 1980s," *Medical Care* 31(7), 581-599.
3. For a description of precision engineering at LLNL, see the article beginning on p. 16 of the January 1986 *Energy and Technology Review* (UCRL-52000-86-1), and for a more comprehensive description of the philosophy, capabilities, and accomplishments of precision engineering at LLNL to that point, see the entire September 1987 issue of *Energy and Technology Review* (UCRL-52000-87-9).

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